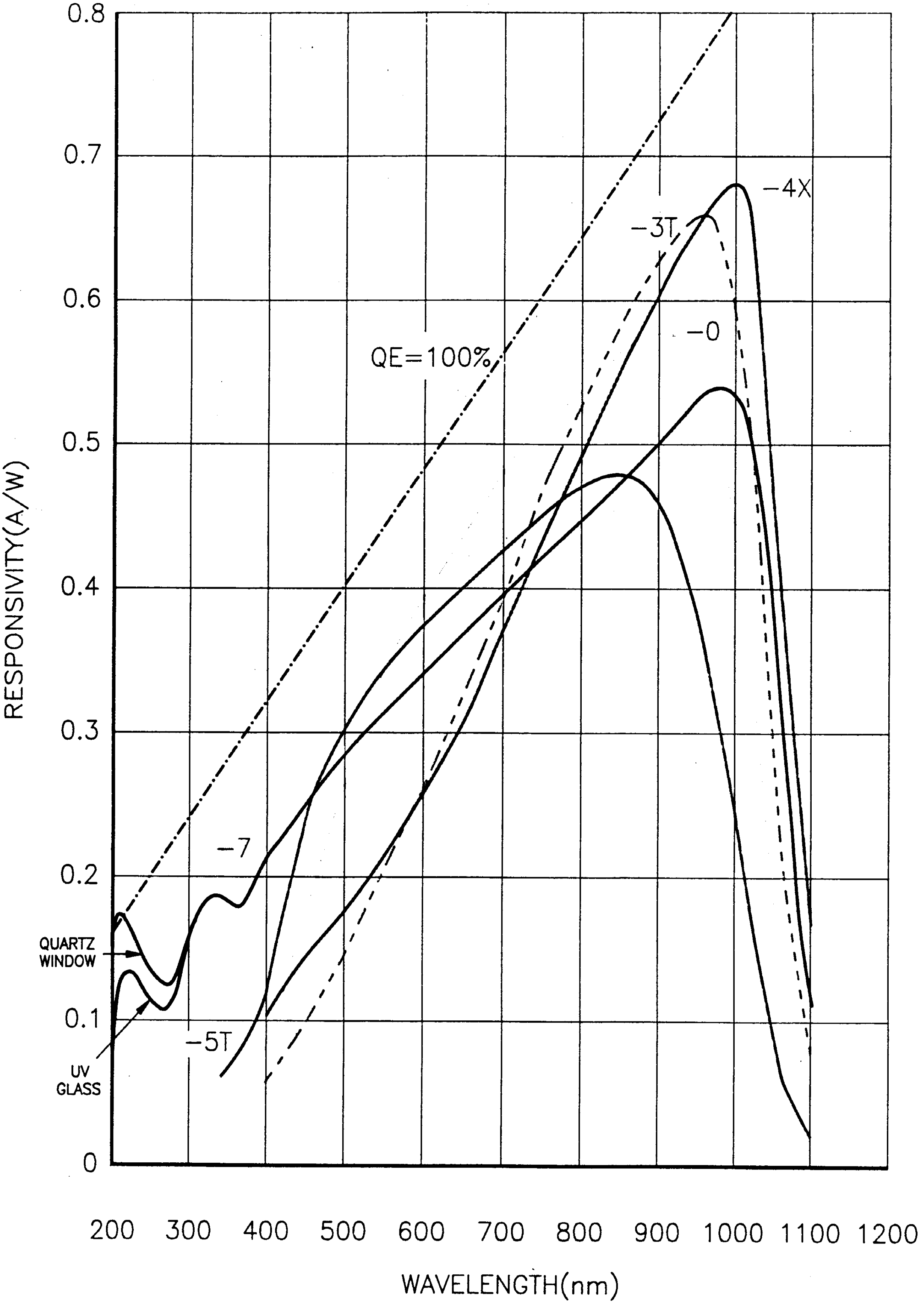
Photodiode Response Curves

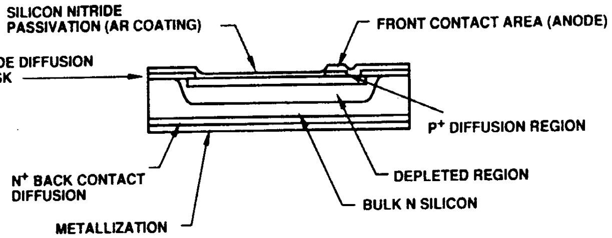


Making the Right Choice

Silicon Photodiode Structure and Operation

An understanding of the diode structure, in particular the behaviour of the depletion layer, is required to make the best use of a silicon photodiode in any given application.

Fig. 2.



The junction region is produced by diffusion or ion implantation of boron into selected areas of the surface of a high resistivity n-type silicon wafer. The geometry of this is accurately defined by a silicon dioxide layer having windows etched in it using standard photolithographic techniques. A heavily doped n-type layer is introduced into the rear face when the device is to be operated in the fully depleted mode, which will be described later. A silicon nitride passivation layer is deposited onto the front face, the thickness being chosen so that the layer acts as an antireflection coating for the wavelength of operation. The front contact is normally by means of a photolithographically defined aluminium layer and the rear contact is by means of one of a number of alternative multilayer metallisations.

Between the p-type region and the lightly doped n-type region there is a depletion region which is free from mobile charges. The width of this region depends upon the resistivity of the silicon and the applied voltage; even with no externally applied bias the diffusion of electrons and holes across the junction creates a depletion region with an electric field across it which is known as the "built-in" field.

When a photon is absorbed in a semiconductor an electron-hole pair is formed. Photo current results when photon-generated electron-hole pairs are separated, electrons passing to the n-region and holes to the p-region. Alternatively, holes and electrons may recombine, thereby causing no charge displacement and thus no contribution to photocurrent. There is a greater probability of separation of a photon-generated electron-hole pair when it is formed within the depletion region where the strongest electric field exists.

The primary parameter defining the sensitivity of a photodiode is its quantum efficiency, (QE) which is defined as the percentage of incident photons generating electron-hole pairs which subsequently contribute to the output signal. Quantum efficiencies in the region of 80% are usual for silicon detectors operating at wavelengths in the 800-900 nm region.

The sensitivity of a photodiode may also be expressed in practical units of amps of photodiode current per watt of incident illumination. This parameter, usually known as responsivity (Rλ), may be derived by multiplying the Q.E. by the electronic charge (e) and dividing by the photon energy for a particular wavelength, $\frac{hc}{\lambda}$.

In practical terms:

$$R\lambda \text{ (in A/W)} = \frac{\text{Q.E.(\%)} \times \lambda \text{ (microns)}}{124}$$

This relationship leads to a tendency for responsivity to reduce as the wavelength becomes shorter. For example, at 900nm, 80% Q.E. represents a responsivity of 0.58 A/W, whereas at 430nm, the same Q.E. gives only 0.28 A/W.

Cut off at long wavelengths occurs for a silicon photodiode at a wavelength of 1.1 µm where the photon energy is just sufficient to transfer an electron across the silicon band gap. As this wavelength is approached the probability of photo absorption decreases rapidly with increasing wavelength. In Figure 3 absorption coefficient α is plotted against wavelength for two different temperatures. It will be noted that the absorption coefficient increases with increasing temperature leading to an increase in long wavelength responsivity with temperature.

The penetration depth for 90% absorption has also been calculated from the absorption coefficient data and plotted against wavelength. For wavelengths less that 400nm 90% absorption occurs at depths of less that 0.5µm, whereas at the laser wavelength of 1064nm a silicon thickness of 1mm would be required, and at 1100nm 5mm for 90% absorption. These widely differing absorption depths result in very different design constraints on detectors intended for use at opposite ends of the spectrum.

Fig. 3.

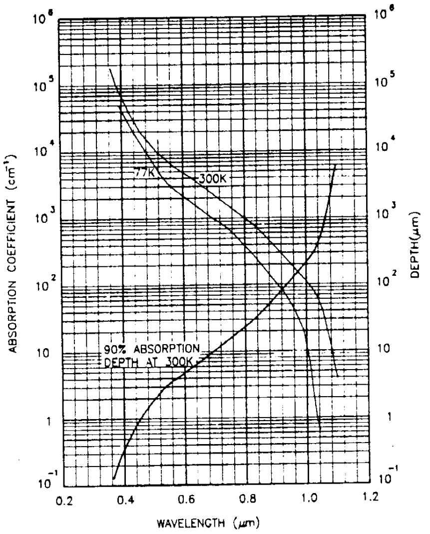


Figure 1 page 2 shows responsivity plotted against wavelength for the various standard Centronic device families. The line representing 100% quantum efficiency is also shown. In practice the attainable responsivity is also reduced by reflection losses from the surfaces of any window used.

Making the Right Choice

Since dark current increases and shunt resistance decreases with increasing temperature, it is important to consider the values of these parameters at the maximum operating temperature for a system. It is usually stated that dark current doubles for every 10°C increase in temperature; however, since the dark current is made up of several components having different rates of change, the net result may vary between doubling every 7°C and doubling every 15°C dependent upon the device design.

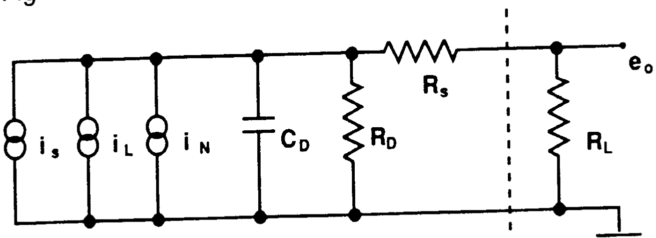
Diode Configuration

Detectors can be produced with an almost infinite variety of geometries within the limits of the resolution of the photolithographic process, and the availability of appropriately sized silicon. To cite two extremes of size, Centronic have produced the visible detectors for weather satellites each having four active areas 80 µm square, and in contrast have supplied NPL with quadrant detectors of 1500 mm² sensitive area for use in their cryogenic absolute radiometer. Arrays of large numbers of elements may be produced having performance characteristics similar to those available for individual discrete detectors. Minimum spacing between elements is dictated by considerations of crosstalk and inter-element leakage, and has to be increased where high resistivity silicon is used, to allow for the effects of sideways depletion around the junctions. Crosstalk results from lateral transistor action between elements and may be below 0.5% at 630 nm, but is typically 2-3% at 1064 nm. Typically minimum spacings of 25 µm are used with low resistivity (150-300 ohm cm) silicon, while spacings of 200 microns maybe necessary for detectors using high resistivity silicon which are designed for high voltage operation.

Conclusion

A brief outline has been given of the factors limiting silicon photodiode performance. Work is continuing on the improvement of short wavelength response, the reduction of dark leakage current and increase of shunt resistance and on the production of higher speed devices to operate at relatively low voltages.

Fig. 7.



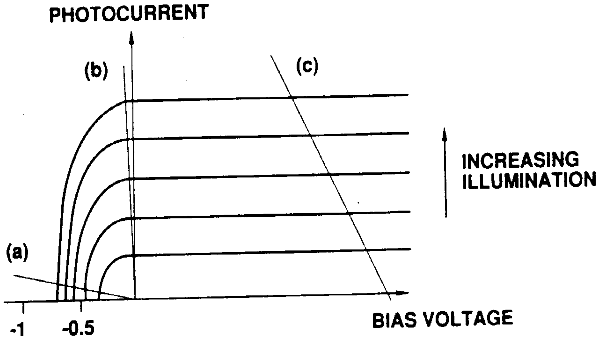
i_s = signal current
i_L = leakage current
i_N = noise current
C_D = diode junction capacity

R_o = diode parallel shunt resistance
R_s = diode series resistance
R_L = load resistance
$e_o = (i_S + i_L + i_N)\,\dfrac{(R_L\,R_D)}{(R_L + R_D + R_S)}$

Operating Circuits

The equivalent circuit of a photodiode is shown (Fig. 7.). Fundamentally a photodiode is a current generator. The junction capacitance of the diode depends on the depletion layer depth and hence bias voltage, being large at zero bias and decreasing by a factor typically greater than 5 as a reverse bias voltage is applied. The value of the shunt resistance is usually high (megohms) but it is an inverse exponential function of forward voltage. The series resistance is low, this being a design function of the diffusion processes and terminations. The effect of the load resistor value (Fig. 8) on the current/voltage characteristics is discussed below.

Fig. 8.



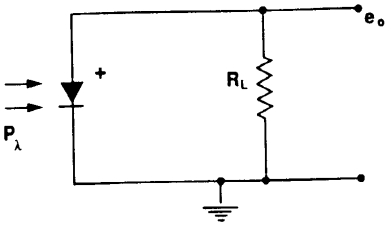
Zero Bias Operation

The term photovoltaic is commonly used to describe operation of a photodiode without application of an external bias voltage. However, a photodiode may be operated in two distinct modes dependent upon the value of the external load resistance R_L.

(a) $R_L >> R_D$ (Fig. 8 Load Line (a))

The generated photocurrent flows through R_D (Fig. 6) causing a voltage across the diode. This voltage opposes the band gap potential of the photodiode junction, forward biasing it. Hence the value of R_D drops exponentially as the illumination increases. Thus the photo-generated voltage is a logarithmic function of incident light intensity. The major disadvantage of this circuit is that the signal depends on R_D which typically has a wide spread of values over different production batches. The basic circuit is shown in Fig. 9

Fig. 9.

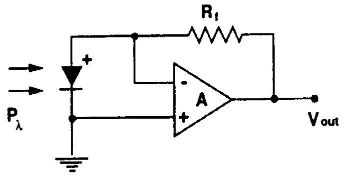


(b) $R_L << R_D$ (Fig. 8 Load Line (b))

Best advantage may be taken of a photodiodes behaviour as an extremely linear current generator if it is operated into a very low resistance in comparison with the diode shunt resistance.

The generated photocurrent flows through R_L which is fixed. The resultant voltage is therefore linearly dependent on the incident radiation level. One way of achieving sufficiently low load resistance, but with an amplified output voltage is by feeding the photocurrent to the virtual earth input of an operational amplifier circuit as shown (Fig. 10). This circuit has a linear response and gives low noise due to the almost complete elimination of leakage current but is slow as explained in the Section on Speed of Response, on page 4.

Fig. 10.



Reverse Biased Operation (Fig. 8 (c))

If a high speed of response is required a photo diode is best operated with reverse bias in the photoconductive mode. The generated photocurrent produces a voltage across a load resistor (see load line (c) Fig. 8), in parallel with the shunt resistance. Since, in the reverse biased mode R_D is substantially constant, large values of R_L may be used still giving a linear response between output voltage and applied radiation intensity. The main disadvantage of this mode of operation is the increased leakage current due to the bias voltage, giving higher noise than the other circuit modes already described. Practical photoconductive mode circuits are shown in Figs. 11 and 12.

Fig. 11.

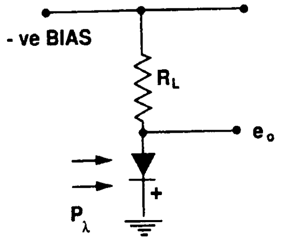
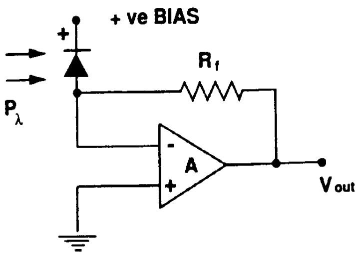


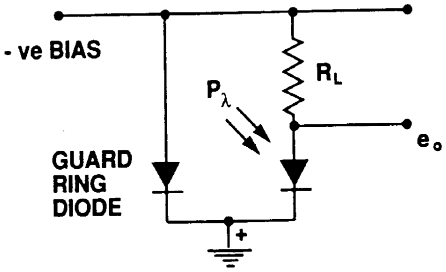
Fig. 12.



Use of a Guard Ring

A guard ring structure is provided on certain photodiode intended for high voltage operation and takes the form of a isolation ring surrounding the active area. When this i biased at a similar potential to the photodiode then th surface leakage current from the periphery of the active are is minimised. A guard ring offers most significant benefi when it is necessary to operate at very high bias voltage an has little or no effect in most cases below about 50 volts. typical operating circuit is shown in figure 13. The guard rin may be left unconnected if its use is not required.

Fig. 13.



Diode Polarity

A photodiode has two terminals, a cathode and an anode. has a low forward resistance (positive voltage applied anode) and high reverse resistance (negative to anod Normal biased operation (Fig. 11) of most diodes describ in this catalogue requires negative biasing of the active are which is the anode with positive bias to the cathode, whi forms the rear face of the silicon diode chips.

Under zero bias operation (Figs. 9 and 10) the generate current is in the reverse direction whilst the anode generate a positive voltage which is thus opposite in polarity to th applied externally in the reverse biased mode. The circuit figure 9 generates a positive output voltage and that in figu 10 a negative output.

Hybrid Photodiode/Amplifiers

Centronic produces a range of standard photodiode - amplif combinations in similar packages to those used for t photodiodes. Apart from a reduction in size these circu offer the benefits of reduced noise pick up and amplif generated noise as a result of the reduction of st capacitance, shorter interconnections and screening of sensitive amplifier input points. A hybrid circuit offers gr benefits where low noise is required in conjunction with h transimpedance gain or high frequency operation.

Please consult the factory for data sheets covering t Centronic hybrid range.

Making the Right Choice

A device such as one of the Centronic -7 series, which is designed primarily for blue and ultraviolet sensitivity requires a very shallow junction so that the depletion layer extends as close as possible to the surface. Special precautions are taken to minimise the density of recombination centres near the surface to allow collection of a high proportion of carriers generated in the p-type region above the depletion layer. Careful choice of antireflection coating material is necessary since coatings suitable for longer wavelengths often strongly absorb ultraviolet radiation. At very short wavelengths photon energies are high enough for the generation of more than one hole electron pair per photon which allows quantum efficiences of greater than 100% to be achieved. Devices such as the Centronic 4Xseries which are designed for high pulsed responsivities at long wavelengths require use of a deep depletion layer. This is achieved by the use of very high resistivity silicon wafers, with high operating voltages.

Since at the YAG laser wavelength of 1.064 microns a significant proportion of the radiation would not be absorbed within a standard silicon thickness of 380µm a reflective back metallisation layer may be used to allow the generation of additional hole electron pairs as the residual radiation passes back into the silicon. The inherent disadvantages arising in a device designed for maximum sensitivity at long wavelengths are a higher dark current and higher noise figures, resultant both from the high operating voltage and use of high resistivity silicon. Response times are inherently slower due to the longer transit distances for holes and electrons.

Speed of Response

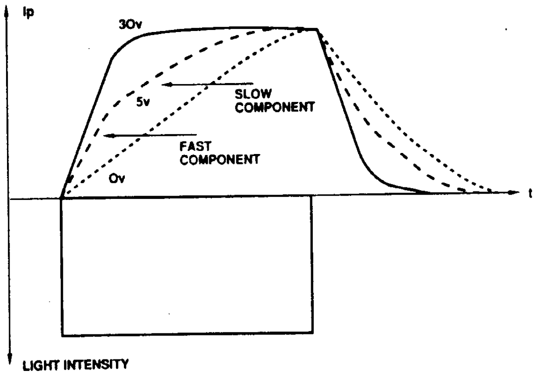
In many applications it is the dynamic performance which is of greatest interest. The photodiode response time is the quadrature sum of the charge collection time and the RC time constant effect arising from the series plus load resistances and the junction plus stray capacitances.

Charge collection time is voltage dependent and is made up of a fast and a slow component. The fast component is produced by transit of electrons and holes through the depletion region, at their respective drift velocities, under the influence of the electric field.

Photon energy absorbed outside the depletion region will produce carriers that are collected by diffusion and the response time of these carriers will be relatively slow. Figure 4 illustrates the transient response of a photodiode to a square pulse of radiation.

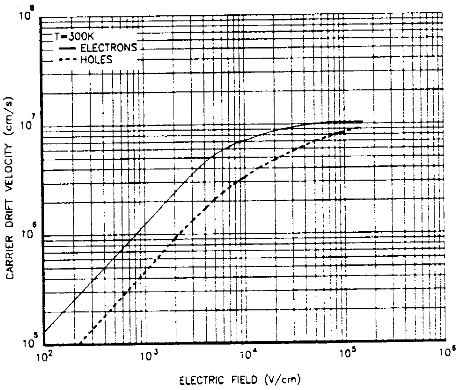
When a diode is operated in the unbiased mode, the diffusion component dominates giving risetimes of the order of 0.5 µs dependent upon operating wavelength and hence absorption depth.

Fig. 4.



For a fast response time, silicon resistivity and operating voltage must be chosen to give a depletion layer width such that the majority of the carriers are generated within it at the operating wavelength. In this case transit time will be dependent on both electron and hole drift velocities. Figure 5 illustrates the way drift velocity increases with electric field and it will also be seen that, except at very high fields the electron velocity is 2.5 times that for holes. Hence, hole transit time tends to dominate.

Fig. 5.



Since the depletion depth necessary for full absorption increases rapidly with operating wavelength, transit times increase correspondingly. It is, therefore, difficult to achieve risetimes faster than 15 - 20 ns at 1064nm, whereas times of 2ns downwards are available at or below 900 nm.

Advantage may be taken of the increase in drift velocity with electric field by use of a fully depleted design such as one of the - 3T or - 4X series. In this structure silicon thickness is reduced to just contain the required depletion depth, and a heavily doped back layer is used to supply the necessary charge to support the depletion region at higher voltage. In this way the operating field, and hence the carrier drift velocities, may be increased without a significant increase in depletion depth.

Further increases in speed may be obtained at the expense of overall sensitivity by use of silicon which is not thick enough to allow full absorption of incident radiation.

Making the Right Choice

The junction capacitance of a photodiode is analogous to a parallel plate capacitor in which the spacing between the plates is a function of applied voltage. The capacitance is therefore proportional to junction area and decreases with increasing bias voltage until full depletion occurs.

In practical terms, $C_j = 1.06 \frac{A}{W}$ pF (where A is in cm^2 and W in cm)

Although much work is in progress on the attainment of faster diode response at lower operating voltages, in many applications response time is limited by the RC time constant, resultant from the combination of the detector capacitance and series resistance plus load resistance in the operating circuit.

Minimum Detectable Power

In many design applications, the designer is concerned with the minimum detectable power of a photodiode. The minimum incident power on a photodiode required to generate a photocurrent equal to the total photodiode noise current is defined as the noise equivalent power, or NEP. As a mathematical expression this may be written as

$$\text{NEP} = \frac{\text{RMS noise current (A)}}{\text{Photodiode sensitivity (A/W)}}$$

The NEP is dependent on the bandwidth of the measuring system; to remove this dependence the figure is divided by the square root of the bandwidth. This gives an NEP density in watts/Hz $^{\frac{1}{2}}$. Since the power to current conversion of a diode depends on radiation wavelength, the NEP figure is always quoted at a particular wavelength.

The noise generated by a silicon photodiode, operating under reverse bias, is a combination of shot noise, due to dark leakage current, and Johnson noise due to the shunt resistance of the device at the ambient temperature. The shot noise current produced by the reverse leakage current of a device is given by the formula

$$I_S = (2e\, i_D B)^{\frac{1}{2}}$$

where I_S = shot noise current
e = electronic charge (1.6×10^{-19} coulomb)
i_D = dark leakage current (amps)
B = bandwidth of system

The Johnson noise contribution is provided principally by the shunt resistance of the device. The Johnson noise current is given by

$$I_J = \left(\frac{4KTB}{R}\right)^{\frac{1}{2}}$$

Where I_J = Johnson noise current (A. RMS)
k = Boltzmann constant (1.33×10^{-23}J/K)
T = absolute temperature (K)
R = Resistance giving rise to noise

The total noise current is the quadrature sum of the individual noise current contributions.

$$I_N = (I_S^2 + I_J^2)^{\frac{1}{2}}$$

and $$\text{NEP} = \frac{I_N}{R\lambda}$$

As an example; if a diode has $I_D = 2$nA, a shunt resistance of 5×10^8 ohms and responsivity $(R\lambda) = 0.5$ A/W, then for B = 1 Hz:

Shot noise current	$I_S = 2.5 \times 10^{-14}$A
Johnson noise current	$I_J = 5.6 \times 10^{-15}$A
Total noise current	$= 2.6 \times 10^{-14}$A
NEP	$= 5.1 \times 10^{-14}$W

Thus it will be seen that shot noise is the dominant compon for a reverse biased photodiode especially for a large area device operated at a high voltage. If a device is operated with zero bias, then the Johnson noise dominates, since the dark current tends to zero. It is usually the case when operating in this mode that noise current is reduced to such a degree that the NEP, and hence the minimum detectable signal, is reduced in spite of some loss of absolute sensitivity.

Temperature Effects

Figure 6 illustrates the typical variation of Responsivity with Temperature for Centronic series 0, 3T, 5T and 4X detectors. It should be noted that -7 series devices show a small positive temperature coefficient at short wavelengths.

As silicon resistivity is reduced the dark current decreases and dynamic (or shunt) resistance increases at the expense of increased capacitance for a given operating voltage. This trade off of dark current against capacitance becomes obvio upon comparisons of the catalogue data for Centronic - 5T series devices with - 3T series for example.

Fig. 6.